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# CAN MEMS TECHNOLOGY PROVIDE SWITCHING COMPONENTS NECESSARY FOR NEXT GENERATION RADAR SYSTEMS? (U)

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## ABSTRACT (U)

(U) This paper will inform the reader of how the use of MEMS switches in radar systems has the potential for significant performance improvements. The need for improved radars is defined with a description of one technology driver of MEMS switches. MEMS switch technologies are introduced to establish a foundation of knowledge for the rest of the paper.

(U) Significant research has been done in the area of applying MEMS technologies to radar systems. The reader will find information on four MEMS capacitive shunt switches, which were devised at the University of Michigan. The performance of each switch is presented along with the theory behind each device.

## Introduction (U)

(U) The United States military has relied on radar technologies for decades. With no technologies foreseen in the near future to replace this sensor, component improvements are necessary in order for system performance to improve. Why is there a need for improved radars? One specific answer is ground combat vehicle survivability. The U.S. Army research and development community is currently engaged in a rigorous challenge to mature technologies that will allow designers to engineer a vehicle weighing a quarter the weight of the M1 Abrams main battle tank, yet be just as survivable. Microelectromechanical systems (MEMS) may hold the key to developing a radar for use in systems offering the survivability of today's main battle tank on a platform a fraction of the weight.

## Technology Driver (U)

(U) One of the most stressing cases on this requirement is protecting a vehicle against kinetic energy (KE) weapons. These munitions, fired from the main gun of tanks, travel

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at speeds in excess of one kilometer per second. Active protection systems are in development to destroy KE rounds at a distance sufficiently far from the defended vehicle to assure its survival. Testing has shown that redirecting and/or breaking the incoming threat into small pieces is possible and can provide the level of protection required for the Army's next generation of combat vehicles. However, in order to intercept the threat, it must first be detected and tracked. The minute radar cross section of a KE round makes this task even more stressing. If a conventional, mechanically steerable radar is used for this job, it must first take the time to slew itself in the direction of the threat. The slewing of the radar will occur all the while the threat flies closer and closer to the vehicle. Analysis has shown that the incoming round must be detected approximately 1.5 km away from the defended vehicle to allow the other components of the system to respond accordingly. This includes threat tracking, trajectory computation to determine the ideal intercept point, slewing of the launcher, and countermunition fly-out.

(U) Four stressing demands for an active protection system radar have been identified: KE round velocity, slewing time for the radar to point in the direction of the threat, threat radar cross section, and detection range. New technologies must be considered as solutions to these problems, as none of them are trivial to resolve. Mechanical gimbals are susceptible to gravity as well as shock and vibration, which can cause mechanical failure. An electronically scanning, also known as e-scan, antenna would not experience the same drawbacks and also has the ability to track multiple targets, simultaneously. E-scan radars work by configuring multiple waveguides in either a one or two dimensional array, depending on the desired field of regard. The radio frequency (RF) signal is sequentially transmitted out of the waveguides with slightly offset phases. Depending on how the phases occur, a beam can scan ± 60° from a flat array (see Figure 1) (ref. 1). Four arrays can be integrated around a vehicle to provide 360° of azimuth scanning coverage. Roughly one second is required for a mechanically slewing antenna to redirect its beam 100°. An e-scan antenna is capable of covering the same angle in less than a millisecond (ref. 1). This performance also enables the radar to be used for communications, combat identification (friend versus foe), and weapon guidance. Every one of these is important for the Army's future combat vehicle systems.

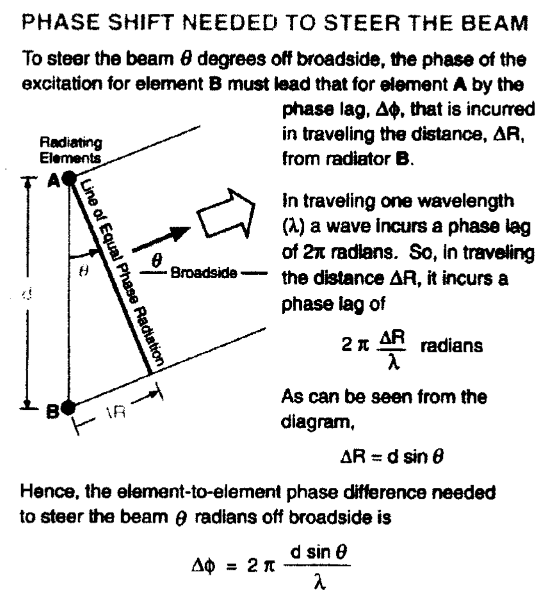


Figure 1. (U) Electronically Scanning Array Antenna Operation (ref. 1).

(U) One of the key components of an e-scan radar is the switch. Selecting which phase shift to apply to a given signal line is critical and must be done quickly while introducing as little noise as possible. MESFETs and PIN diodes are the current leaders in technological capabilities, but MEMS has shown potential as a replacement for these components (see Table I).

TABLE I. (U) Switch Performance Comparison (ref. 2).

**RF MEMS vs. PIN AND MESFET SWITCH COMPARISON**

| | MESFET | PIN Diode | MEMS |
|---|---|---|---|
| Series resistance (Ω) | 3 to 5 | 1 | < 1 |
| Loss at 1 GHz (dB) | 0.5 to 1.0 | 0.5 to 1.0 | 0.1 |
| Isolation at 1 GHz (dB) | 20 to 40 | 40 | > 40 |
| IP3 (dBm) | 40 to 60 | 30 to 45 | > 66 |
| 1 dB compression (dBm) | 20 to 35 | 25 to 30 | > 33 |
| Size ($mm^2$) | 1 to 5 | 0.1 | < 0.1 |
| Switching speed | ~ ns | ~ µs | ~ µs |
| Control voltage (V) | 8 | 3 to 5 | 3 to 30 |
| Control current | < 10 µA | 10 mA | < 10 µA |

<u>Switch Overview (U)</u>

(U) MEMS switches can be classified in four ways:

- series or shunt
- fixed-fixed beam, cantilever beam, or compliant beam
- capacitive or metal-to-metal contact

- actuation power source

Although each category is independent of the rest, only a limited number of switch varieties have come to fruition. The most significant benefits and drawbacks for each type of switch will be presented as its respective category is introduced.

(U) Series versus shunt type describes how the switch acts in the circuit it is controlling (see Figure 2). In a series switch, the switch is directly inline with the transmission lines. The signal flows through the transmission lines while the switch is on, or closed. While the switch is off, the circuit is open, preventing any signal passage. In a shunt configuration, the switch is located in parallel with the transmission lines. Under open conditions, the switch presents very little disturbance to the transmission, allowing the signal to pass. However, in the on state, the switch creates a shunt to ground and the signal flow is blocked.

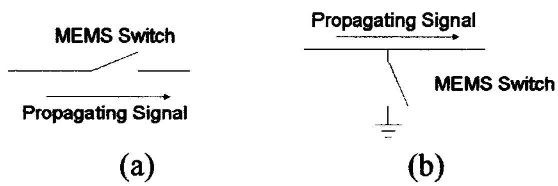


Figure 2. (U) Circuit Equivalent of a Series Switch (a) and Shunt Switch (b).

(U) As compared to solid-state devices, MEMS shunt switches offer significant advantages. Among the advantages are minimal DC power consumption, large capacitance differentials between on and off states, very low intermodulation products, and fabrication ability on almost any substrate. On the other hand, the MEMS devices switch states slower, require high actuation voltages, and do not handle power over 2 W well (ref. 3). The limited power handling capability of MEMS switches is a significant drawback that may prevent these switches from being applied to Army needs. The next categorization describes the physical properties of the switch.

(U) A fixed-fixed beam describes a switch where a bridging structure is connected to the substrate at either end and traverses a coplanar waveguide (CPW). The waveguide is isolated by the air gap between itself and the bridge across it (see Figure 3). Actuation of the switch causes the bridge to buckle and contact the CPW. A 1000-2000 Å dielectric material is often applied to the lower electrode preventing metal-to-metal contact (ref. 3). The intrinsic stress in the bridge prevents the bridge from collapsing onto the CPW, while in the off state (ref. 5). This stress also overpowers stiction forces when the switch is no longer actuated.

Figure 3. (U) SEM Picture of a Fixed-Fixed Beam MEMS Switch (ref. 6).

(U) A cantilever beam configuration is very similar to a fixed-fixed beam design, except only one side of the beam is fixed to the substrate. In the off state, the beam provides no electrical contact between transmission lines or very little capacitance is seen by the transmission lines, depending on what type of switch it is. Once actuated, the beam deflects and either makes an electrical contact between lines or introduces significant capacitance into the lines, again, depending on the type of switch it is. This design offers a lower spring constant than the fixed-fixed design, because only one side of the beam is secure. Cantilever beams have a special purpose in many sensing applications, but for switching, fixed-fixed beams are to some extent easier to work with, because they are stiffer and more robust than cantilever beams (ref. 7).

(U) A compliant beam switch differs from the other types in that the area of interest, that which contacts a transmission line or generates capacitive coupling, is not the portion experiencing stress from deflection. Instead, a pad, or membrane, is suspended in the air via support members (see Figure 4). These members are specifically designed to have a lower spring constant than fixed-fixed or cantilever beams. In the on state, the support members deflect bringing the pad in contact with or in very close proximity to the transmission line(s). In the off state, the membrane sets isolated from the transmission line, similar to the fixed-fixed and cantilever beams.

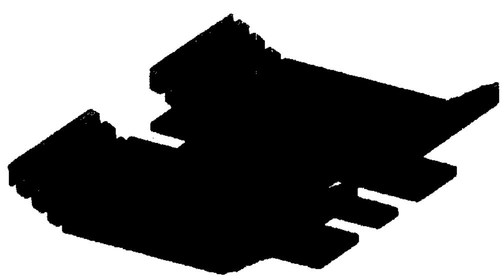

Figure 4. (U) Model of a compliant beam switch with stresses under actuation highlighted (ref. 8).

(U) The mechanical design of the switch has a significant impact on pull-down voltage, but three approaches can be used on any design to lower the necessary voltage. They are:

- increase the area on which the voltage is applied
- decrease the deflection distance necessary to transfer from one state to the other
- design the switch to have a lower spring constant (ref. 5).

Increasing the area is feasible, except that size is one significant advantage of MEMS devices. Any change in size must be done within reason to maintain this benefit. A smaller deflection distance can introduce multiple problems, so any alterations, again, must not be taken too far. Stiction issues can arise if the switch is a cantilever beam. Smaller gaps mean tighter fabrication tolerances, putting more strain on the manufacturing process. Also, capacitance difference between on and off states of the switch is a critical circuit parameter. Decreasing the gap would vary the capacitive coupling, so the change would have to be accounted for elsewhere in the system. Additionally, RF signal return loss restricts the gap to be in the area of 1-2 µm (ref. 5). Further categorization can be done based upon component contact under actuation.

(U) A capacitive switch alternates between acting like a transmission line and acting like a capacitor. In the open state, the passing signal flows through the switch, unimpeded. When the switch is actuated, though, the transmission line and its electrical ground line are brought in very close proximity, with only a thin dielectric in between. To the transmitting signal, this is a capacitor. The air gap, as well as the dielectric covering the transmission line, determines the open-to-closed capacitance ratio and the switch isolation (ref. 5).

(U) A metal-to-metal contact switch acts as its name implies. A metal coating is applied to the moving surface and, under on state conditions, it connects both transmission lines. The metal-to-metal contact completes the circuit and the signal flows accordingly. Figure 5 shows a metal-to-metal contact switch designed by Rockwell Science Center, Thousand Oaks, California.

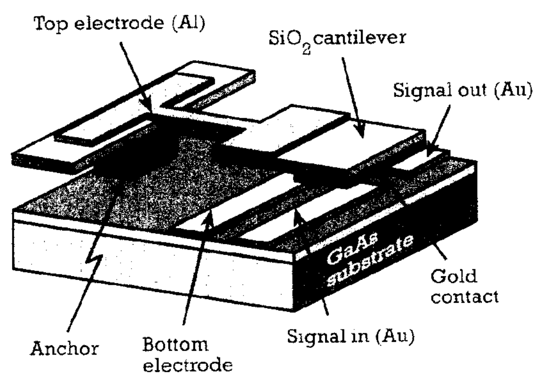


Figure 5. (U) Cantilever Beam, Metal-to-Metal Contact MEMS Switch (ref. 9).

(U) Both capacitive and metal-to-metal switches experience repetitive striking between surfaces. This is a major contributor to short life expectancy. In the case of capacitive switches, the dielectric separating the transmission lines and the bridge can deteriorate, altering the capacitance of the switch. The high isolation attained in the on state must be maintained for the switch to operate effectively, but is jeopardized by the impact between bridge and dielectric. In the metal-to-metal case, the contact between the deflecting metal and the transmission line is critical, because this contact must have the capacity to pass current. Contact depletion can occur under use, increasing the resistivity of the switch and, thus, increasing operating temperatures.

(U) Operational simplicity is on the side of the metal-to-metal switch. That is one major reason why it was the first design to be demonstrated. One drawback to the design, however, is its current handling ability. A single contact switch can only handle current up to about 1 mA, but double-contact designs have proven more capable. A double-contact switch employs two separate contact points rather than using just one (ref. 10). A minimal current handling ability is detrimental to a switch's potential use in RF systems. High power, high bandwidth radars capable of meeting active protection system requirements rely on the ability to transmit over one watt of power.

(U) All of the described switches have one thing in common--they are all mechanical in nature. Therefore, a source of energy is needed to induce motion. Hydraulic, pneumatic, and thermal energy, along with shape-memory alloys are all viable options to power these switches, but are not practical for RF applications due to speed, processing complexities, and other factors (ref. 9). Electrostatic or electromagnetic forces are generally used in the commercially available switches on the market today (ref. 11).

(U) Electrostatic actuation does require higher actuation voltages than electromagnetic switches, but the latter requires somewhat more extensive processing, since a thin magnetic film must be applied (ref. 11). Electrostatic switches typically run on only a few microwatts of power. Additionally, due to their simplicity in biasing, they are superior to comparable solid state PIN diodes or FET transistors (ref. 12). Electrostatic switches have been designed to operate anywhere from a few volts to over 100 V (ref. 5). Laboratory tests have already shown that lower actuation voltages lead to a longer life expectancy (ref. 12). Fortunately, measures can be taken to alter the required voltage, as described above.

## Examples (U)

(U) When designing a switch, one must choose the applicable characteristics outlined above based upon how the switch will be implemented. The series metal-to-metal switch and the shunt capacitive switch are at the forefront of MEMS switch research (ref. 3). The shunt capacitive switch with fixed-fixed beams has extensive potential for use in RF systems, including radars, and is therefore ambitiously researched in the MEMS community. Significant work in this area has taken place at the University of Michigan by Jeremy Muldavin and Gabriel Rebeiz.

## Shunt Capacitive Fixed-Fixed Switch (U)

(U) The team of Muldavin and Rebeiz have designed a variety of CPW shunt capacitive switches (see Figure 6). One such switch was designed and simulated with the intent of operating in the frequency range of DC-40 GHz. The bridge length is 300 μm and spans a CPW 100 μm wide. The gap through which the bridge must travel when actuated varies between 1.5 μm and 4 μm, for experimentation purposes. Bridge widths vary between 20 μm and 140 μm, also for experimental purposes. Reasonable pull down voltages for this type of switch design are 12-25 V. According to the pair, 5–20 μs switching times are valid for this configuration. The resulting calculated capacitance ratio is 60:1 and 120:1 for gaps of 1.5 μm and 4 μm, respectively. Down state isolation of better than 20 dB was seen at frequencies above 20 GHz (with a down state capacitance of 2.7 pF). Further work was done on shunt switches exemplifying the benefits of "tuning".

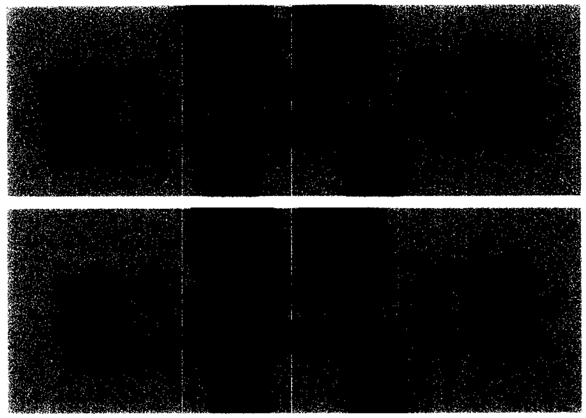

Figure 6. (U) Capacitive Fixed-Fixed Shunt Switch Fabricated at the University of Michigan (ref. 6).

Tuned Shunt Capacitive Switch (U)

(U) The term tuning indicates some measures have been taken to compensate for the LC series resonance of the switch. Muldavin and Rebeiz accomplished this by adding a second bridge to the switch and joining the two switches with a high impedance transmission line (see Figure 7). The design of this line is calculated based on the frequency to be cancelled, connection line impedance, capacitance from the bridge, and port capacitance. The result of tuning is a higher up-state capacitance can be designed into the switch. This allows for designs with increased bridge area, which will improve down-state isolation, and/or a decreased gap between the CPW and the bridge, which will result in a lower pull down voltage. The drawback to increasing the bridge area is that the MEMS device will occupy a larger space, while decreasing the gap decreases the capacitance ratio. Muldavin and Rebeiz opted to decrease the gap, from 3.5 μm to 1.5 μm, to lower the pull down voltage from 50 V to 15 V resulting in a capacitance ratio of about 40:1 compared to about 80:1 with the larger gap. With a down state capacitance of 2.2 pF, isolation of better than 35 dB was achieved. A weakness in tuning is that bandwidth is limited. This design was intended for use between 20 GHz and 40 GHz, but the techniques are applicable up to 100 GHz. The switch design emphasizes the need for compact circuits and simple fabrication to keep the cost of application down. Further strides were taken to increase down state isolation as well as compensate for lost bandwidth due to tuning (ref. 13).

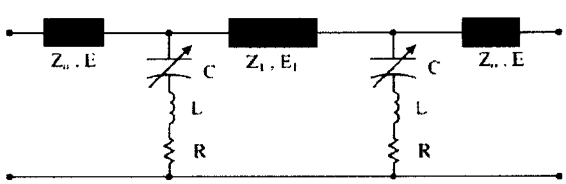


Figure 7. (U) Schematic Representation of a Tuned Capacitive Shunt Switch (ref. 13).

Tuned Cross Switch (U)

(U) Muldavin and Rebeiz were able to improve isolation over a wider bandwidth (around the desired null frequency as well as at lower frequencies) than a single MEMS switch by adding shunt sections to the tuned device. "The shunt sections are open-ended stubs loaded at the ends with a smaller MEMS switch", according to the researchers. Two independent reflection nulls are generated by the set of original bridges and the new set of bridges. The increase in bandwidth is proportional to how spread apart the nulls are. A switch was fabricated and tested. The pull down voltage is 15 V to actuate the switch through the 1.5 µm gap height. Greater than 40 dB of isolation was demonstrated between the frequencies of 17 GHz and 40 GHz and (see Figure 8). A poor capacitance ratio (approximately 22:1) was experienced due to surface imperfections, which limited performance. This switch design has the potential of producing isolations greater than 50 dB for frequencies from 12-40 GHz if more reasonable capacitance ratios (45:1) can be achieved. Adding switches to improve performance is not the only feasible approach for higher isolation over a wider bandwidth. Tuning can also be implemented with a single bridge.

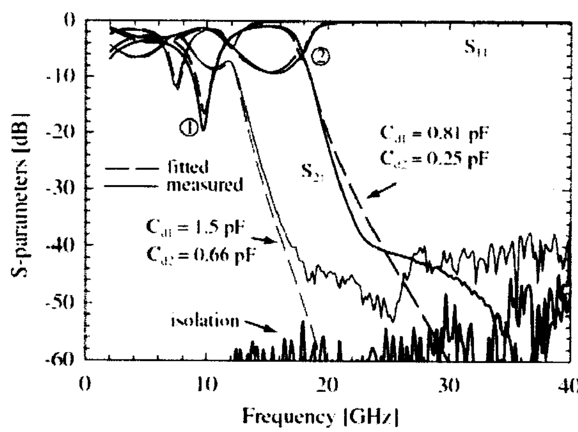

Figure 8. (U) Measured Performance of Tuned Cross Switch (ref. 6).

Specialized Tuned Switch (U)

(U) A reflection null can be created by adding inductance to the bridge via the transmission line length. Muldavin and Rebeiz did just that in order to tune a shunt switch for operation around 12 GHz. They effectively added 37 pH of inductance to the switch at about 12 GHz by adding a 150 µm inductive transmission line. This resulted in isolation of approximately 35 dB at that frequency—an improvement of 8 dB over the untuned design.

Conclusion (U)

(U) The need exists for low cost switches that offer higher performance than is available today. The microelectromechanical system is in its infancy and will require a significant amount of work before it can be considered as a reliable component for active protection radar systems. MEMS technology will attain a maturity level where the potential predicted today will become a reality, but cost will play a significant role in determining whether or not they are put to use. Efforts are underway to meet these demands with various levels of success already seen.

(U) Researchers at the University of Michigan have designed four different capacitive shunt switches: a single bridge switch, a tuned dual bridge switch, a tuned cross switch, and a tuned single bridge switch for the X-band. Table II consolidates the performance demonstrated by these switches. Isolation levels exceeding 40 dB were achieved at 40 GHz and greater than 50 dB was verified at 12 GHz. The data can be directly applied to radar systems in the Ka and X bands, both of which have been pursued by the Army.

Table II. (U) Reported MEMS Capacitive Shunt Switch Parameters

| | A | B | C | D |
|---|---|---|---|---|
| **Pull down voltage (V)** | 12-25 | 15 | 15 | N/A |
| **Capacitance ratio** | 60:1 | 40:1 | 22:1 | N/A |
| **Isolation (dB)** | 20 | > 35 | > 40 | 35 |
| **Down state capacitance (pF)** | 2.7 | 2.2 | 1.5 | 4.8 |

**Legend**
**A - Single Bridge Switch (Simulated)**
**B - Tuned Dual Bridge Switch**
**C - Tuned Cross Switch**
**D - Tuned X-Band Switch**

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# CAN MEMS TECHNOLOGY PROVIDE SWITCHING COMPONENTS NECESSARY FOR NEXT GENERATION RADAR SYSTEMS?

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## Outline

- Introduction
- Technology Driver
- Switch Overview
- Examples
  - Shunt Capacitive Fixed-Fixed Switch
  - Tuned Shunt Capacitive Switch
  - Tuned Cross Switch
  - Specialized Tuned Switch
- Conclusion

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## Introduction

- The United States military has relied on radar technologies for decades.
- There does not appear to be a replacement for radar systems in the near future that will meet the size, weight, power, and cost constraints of ground combat vehicles. New technologies must be considered to continue evolving radars to meet ever-increasing demands on performance.
- One application for radars that will require state-of-the-art performance is ground combat vehicle survivability.

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## Technology Driver

- Active Protection (AP) systems offer the only viable approach for protecting the Army's Future Combat System of Systems (FCS) against Kinetic Energy (KE) penetrators while meeting the integration specifications of the platform.
- A threat, i.e. KE penetrator, must first be detected and tracked before a countermunition can be deployed to intercept the incoming round.
- The KE penetrator places four significant demands on a tracking system:
  - High threat velocity
  - Minimal radar cross section
  - Far detection range
  - Minimal time for sensor slewing
- Radar technology can be employed to meet the above demands.

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## Radar Approaches

Two approaches to radar:

- Mechanically steerable
  - Susceptible to gravity, shock, and vibration
  - Longer timeline to aim
- Electronically scanning (E-scan)
  - More technologically risky
  - Multiple antenna needed for hemispherical coverage
  - Better multi-use capability (i.e. communications, combat identification, weapon guidance, etc.)

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## E-scan Radar Operation

E-scan antenna steer the beam by applying a phase shift to the signal over time. This can direct a beam up to ± 60° from from the flat face of an e-scan antenna (see Figure 1). One way to apply the phase shift is to pass the beam signal through specific phase shifters at precise times. This requires extremely fast switches, which can handle the power of the outgoing signal.

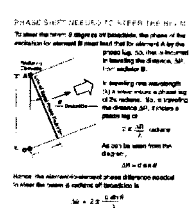

Figure 1. (U) Electronically Scanning Array Antenna Operation (ref. 1).

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# Switch Overview

- Current switching approaches:
  - MESFETs
  - PIN diodes
- Potential switching solution:
  - Microelectromechanical Systems (MEMS)

TABLE I. (U) Switch Performance Comparison (ref. 2).

**RF MEMS vs. PIN AND MESFET SWITCH COMPARISON**

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| Series resistance (Ω) | 3 to 5 | 1 | < 1 |
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| Isolation at 1 GHz (dB) | 20 to 40 | 40 | > 40 |
| IIP3 (dBm) | 40 to 60 | 30 to 45 | > 66 |
| 1 dB compression (dBm) | 20 to 35 | 25 to 30 | > 33 |
| Size (mm²) | 1 to 5 | 0.1 | < 0.1 |
| Switching speed | ns | ns | µs |
| Control voltage (V) | 8 | 3 to 5 | 3 to 30 |
| Control current | < 10 µA | 10 mA | < 10 µA |

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# Switch Overview

**MEMS switches can be classified into four basic categories:**

- series or shunt

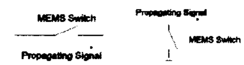


*Figure 2. Circuit equivalent to: series switch shunt switch*

- fixed-fixed beam, cantilever beam, or compliant beam

*Figure 3. fixed-fixed switch (ref. 3) compliant switch (ref. 4)*

- capacitive or metal-to-metal contact
- actuation power source - Hydraulic, pneumatic, and thermal energy, along with shape-memory alloys, electromagnetic, electrostatic

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# Demonstrated Examples

- The series metal-to-metal switch and the shunt capacitive switch are at the forefront of MEMS switch research.
- The shunt capacitive switch with fixed-fixed beams has extensive potential for use in RF systems and is therefore ambitiously researched in the MEMS community.
- Significant efforts are underway throughout the country with a significant backing from Congress in the area of nanotechnology. This report focuses on developments at the University of Michigan.

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# Shunt Capacitive Fixed-Fixed Switch

- Intended operating frequency: DC – 40 GHz
- Bridge length: 300 µm
- Co-Planar Waveguide (CPW) width: 100 µm
- Bridge gap height: 1.5 µm / 4.0 µm
- Pull down voltage: 12-25 V
- Switching time: 5–20 µs
- Calculated capacitance ratio: 60:1 / 120:1
- Isolation: 20 dB (at > 20 GHz)

Figure 4. (U) Capacitive Fixed-Fixed Shunt Switch Fabricated at the University of Michigan (ref. 3).

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# Tuned Shunt Capacitive Switch

- Tuning indicates some measures have been taken to compensate for the inductance/capacitance series resonance of the switch.

- Intended operating frequency: 20 – 40 GHz
- Bridge length: 300 µm
- Co-Planar Waveguide (CPW) width: 100 µm
- Bridge gap height: 1.5 µm
- Pull down voltage: 15 V
- Capacitance ratio: 40:1
- Isolation: 35 dB

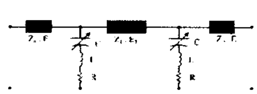

Figure 7. (U) Schematic Representation of a Tuned Capacitive Shunt Switch (ref. 5).

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# Tuned Cross Switch

Offers improved isolation over a wider bandwidth (around the desired null frequency as well as at lower frequencies) than a single MEMS switch by adding shunt sections to the tuned device.

- Intended operating frequency: 12 – 40 GHz
- Bridge length: 300 µm
- Co-Planar Waveguide (CPW) width: 100 µm
- Bridge gap height: 1.5 µm
- Pull down voltage: 15 V
- Capacitance ratio: 22:1
- Isolation: 40 dB

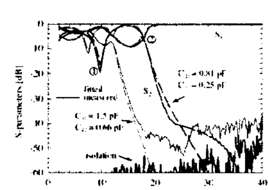


Figure 8. (U) Measured Performance of Tuned Cross Switch (ref. 3).

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## Specialized Tuned Switch

A reflection null was designed in the system to tune a shunt switch for operation around 12 GHz. A 150 μm inductive transmission line added 37 pH of inductance to the switch at about 12 GHz. This resulted in isolation of approximately 35 dB at that frequency—an improvement of 8 dB over the untuned design.

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## Conclusion

- Low cost, high performance switches are needed for next generation e-scan radar systems.
- Microelectromechanical Systems (MEMS) technology offers the potential to meet the needs of state-of-the-art performance demands.
- Existing designs and laboratory results demonstrate that research is progressing in the area of MEMS switches.

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